

# Status of precision MCs

a summary of the [workshop on “Taming the accuracy of event generators”](#), CERN, June 29-July 03, 2020

Snowmass energy frontier workshop, July 21, 2020

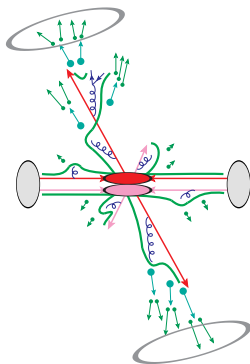
Stefan Prestel (Lund) in collaboration with Silvia Ferrario-Ravasio, Pier Monni, Emanuele Re and Peter Richardson



# Introduction: Event generators

## Ambitions:

- Fully differential, fully exclusive theory tools to produce “test data”.
- Way to imprint knowledge of *all* data onto theory calculations.
- Efficient tools to meet experimental needs.



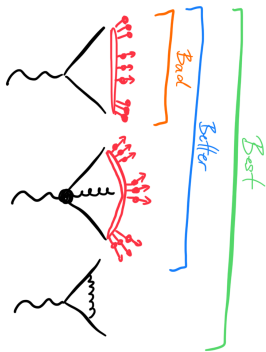
The complexity of the task make event generators intricate combinations of different aspects of particle scattering.

Precision QCD predictions are crucial for LHC, even more so for HL-LHC, FCC & cousins, and also EIC.

# Precision perturbative QCD in event generators

## Why bother?

- Best possible pQCD prediction
  - ⇒ Less wrong collider-specific non-perturbative fits
  - ⇒ More universal data description
  - ⇒ Predictive power
- Large pQCD higher order corrections
  - ⇒ Major part of LHC systematics



## Precision pQCD is produced by matching/merging fixed-order calculations to parton showers

- Parton Showers (PS) generate radiation clouds around primary high-energy particles, i.e. give an initial boost in particle multiplicity
- ⇒ One of the dominant uncertainties for HEP at colliders!
  - ⇒ Progress needed, workshop needed!

# Taming the accuracy of event generators workshop

Context: Matching<sup>1</sup> and merging<sup>2</sup> fields appear to be in a consolidation phase. Recently, much recent in precision all-order parton showers.

<sup>1</sup> combining process-specific higher-order calculations with parton shower and event generator

<sup>2</sup> combining multiple higher-order calculations with each other and with the parton shower

Bring different groups together and discuss

- experimental needs
- perturbative accuracy
- computing performance

...and make progress together.

Slides and videos are available at  
<https://indico.cern.ch/event/876082/>

## Taming the accuracy of event generators

29 June 2020 to 3 July 2020  
CERN  
Europe/Zurich timezone

Overview

Timetable

Contribution List

Participant List

Computer Access

Health insurance, VISA

Directions to and inside CERN

CERN map

TH workshop secretariat  
✉ [thworkshops.secretariat@cern.ch](mailto:thworkshops.secretariat@cern.ch)

At the dawn of the precision era at the LHC, Monte Carlo Event Generators constitute the main bridge between theory and experiments. In this scenario, it becomes paramount to understand quantitatively the perturbative accuracy of the underlying algorithms in view of assessing precisely their theory uncertainty, and of formulating new methods to achieve higher perturbative accuracy in the simulations. In parallel, this theoretical progress crucially requires an efficient exploitation of modern computing technology to address the substantial CPU demand for event simulations at modern collider experiments. The goal of this workshop is to bring together leading experts in the field to analyse recent progress and encourage new collaborations to tackle the main open problems.

**Organizers:** Silvia Ferrario-Ravasio (IPPP, Durham), Pier Monni (CERN), Stefan Prestel (Lund Univ.), Emanuele Re (LAPTH, Annecy), Peter Richardson (CERN).

Application deadline : March 29, 2020 h23:59

Due to the COVID-19 pandemic, the workshop will be divided into two sessions as follows:

- A one-week virtual workshop in the period 29 June - 3 July 2020. This will serve as a kick-off meeting, and to trigger discussions that can be continued in the next session.

# Reality check

- LHC craves multijet merged NLO calculations!
- (HL)-LHC will need even more precision multijets.
- Computing is a severe issue!

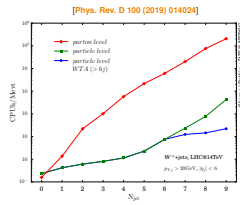
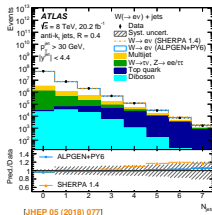
No longer true that detector simulation is the only bottleneck!

More precise calculations also need to be more efficient, if they should be adopted.

Dominant uncertainties: Parton shower and matching scheme.

## (HL)-LHC: a jet factory

- pretty much everything the detector sees is a jet to start with
- excellent understanding of jet modelling and associated theoretical uncertainties is vital
- 'sit back and relax' for data-statistical/experimental uncertainties to drop – except theory



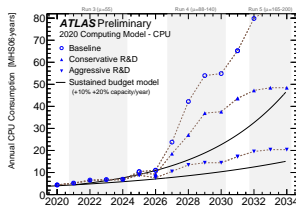
Taming the Accuracy of Event Generators, 29 June 2020

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## Revised computing model

- baseline: assume Run-2 performance (compromise on physics quality)
- conservative: achieve better physics quality for same CPU time / event as in Run-2
- aggressive: CPU time / event halved, generate 30% (simulate 10%) fewer events



# Progress on next-to-leading log-accurate parton showers

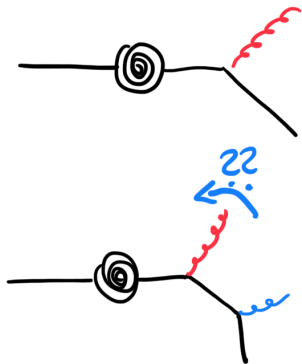
Goal: Highly differential all-order resummation tools for large classes of observables for which NLL determined by emissions of large  $p_\perp$  hierarchy.

Long-standing wish. Much progress in last few years!

- Eikonal structure of single-emission and color coherence must be guaranteed.
- Dominant concern: Showers implement on-shell momentum conservation, but kinematics of subsequent emissions should not distort previous emissions!

⇒ Phase-space mapping (recoil strategy) large focus.

Efforts concentrated at lepton colliders.





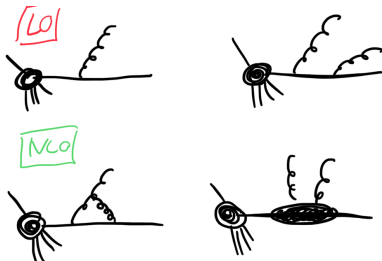
# Progress on NLO parton showers

Goal: Fully differential all-order tool to produce singular parts of QCD emission pattern at  $\mathcal{O}(\alpha_s^2)$  for any scale hierarchy.

Initiated already in 1980's, but reinvigorated in light of NNLO progress in recent years.

- Fully differential  $\mathcal{O}(\alpha_s^2)$ -calculation in **exponent** of Sudakov form factor
- Explicit real-virtual and double-real corrections
- Subtleties: Distinction between ordered and unordered emissions, azimuthal correlations, **relation to and usefulness of  $\overline{\text{MS}}$ -type factorization schemes.**

Efforts mostly at lepton colliders, partial hadron collider results.





# Progress on NLO parton showers

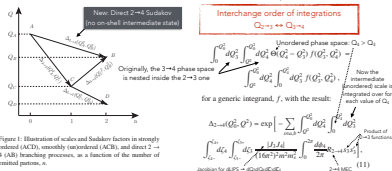
## Getting There: Direct 2→4 Branchings

Li & PS: PLB771 (2017) 59

### Redefine the shower resolution scale

For **unordered** 2→4 paths: scale of 2<sup>nd</sup> branching defines resolution

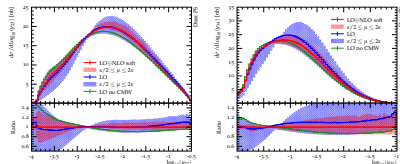
The intermediate on-shell 3-parton state is merely a convenient stepping stone in phase space  $\Rightarrow$  **integrate out**



Note: this is not a very pedagogical exposition, will try to come up with a better one

## Leading color fully differential soft evolution at NLO

[Dulat,Prestel,SH] arXiv:1805.03757



- Impact on 2 → 3 and 3 → 4 Durham jet rate at LEP I
- Uncertainty bands no longer just estimates but perturbative QCD predictions for the first time
- Fair agreement with CMW scheme

ongoing discussions:

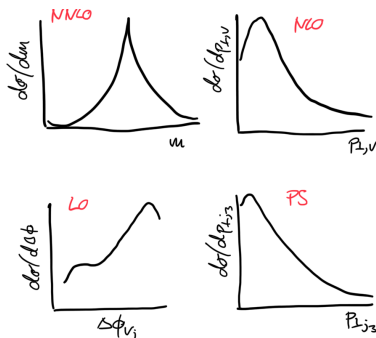
- Relation to NLL efforts, and to NNLO subtraction.
- Accepting factorization schemes with large negative  $\mathcal{O}(\alpha_s^2)$ -corrections
- Defining suitable testing observables.

# Matching event generators to precision fixed-order

Goal: Combine precision fixed-order calculations with event generators.  
Help with next leap in fixed-order precision, i.e. NNLO event generation.

NLO+PS matched and (N)LO multijet merged calculations are a must for SM background predictions. NNLO+PS prototypes available since 2013.

- For precision SM measurements ( $M_W$ ,  $p_{\perp, Z}$ ) NLO needs to be replaced by NNLO
- Provide framework for NNLO event generation
- Subtleties: Not completely differential yet. Impact of shower on inclusive distributions in fiducial phase-space.



NNLO+PS available for DIS and several  $[pp] \rightarrow [\text{color singlet}]$  processes.

# Progress fixed-order pQCD+PS matching

## N<sup>3</sup>LO+PS possible - but useful?

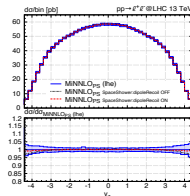
final UN<sup>3</sup>LO+PS cross section

$$\begin{aligned} \langle \sigma \rangle^{\text{un}^3\text{LO+PS}} = & \left[ \tilde{\sigma}_0^3 + \int d\alpha(\alpha) \left\{ (\tilde{B}_1^3 - \tilde{B}_0^3)(1 - \tilde{\pi}_0) + \tilde{B}_1^{\text{VH}}(1 - \tilde{\pi}_0)(1 - \tilde{\pi}_0^{\text{VH}}) \right. \right. \\ & \left. \left. + \tilde{B}_1(1 - \tilde{\pi}_0)(\omega_1 - \omega_1^{\text{VH}} - \omega_1^{\text{VH}} - \tilde{\pi}_0^{\text{VH}} + (\tilde{\pi}_0^{\text{VH}})^2 - \tilde{\pi}_0^{\text{VH}}) \right\} \right] \sigma_0 \\ & + \int d\alpha(\alpha) \left[ (\tilde{B}_2^3 - \tilde{B}_0^3) \tilde{\pi}_0 + \tilde{B}_2^{\text{VH}} \tilde{\pi}_0(1 - \tilde{\pi}_0^{\text{VH}}) \right. \\ & \left. + \tilde{B}_2 \tilde{\pi}_0(\omega_2 - \omega_2^{\text{VH}} - \omega_2^{\text{VH}} - \tilde{\pi}_0^{\text{VH}} + (\tilde{\pi}_0^{\text{VH}})^2 - \tilde{\pi}_0^{\text{VH}}) \right. \\ & \left. + \tilde{B}_2 \tilde{\pi}_0(1 - \tilde{\pi}_0)(\omega_2 - \omega_2^{\text{VH}} - \tilde{\pi}_0^{\text{VH}}) + \tilde{B}_2^{\text{VH}} \tilde{\pi}_0(1 - \tilde{\pi}_0) \right] \sigma_1 \\ & + \int d\alpha(\alpha) \left[ \tilde{B}_3 \tilde{\pi}_0 \tilde{\pi}_0(\omega_3 - \omega_3^{\text{VH}} - \tilde{\pi}_0^{\text{VH}}) + \tilde{B}_3^{\text{VH}} \tilde{\pi}_0 \right] \sigma_2 \\ & + \int d\alpha(\alpha) \tilde{B}_3^{\text{VH}} \tilde{\pi}_0 \sigma_3 + \int d\alpha(\alpha) \tilde{B}_3 \tilde{\pi}_0 \sigma_3 \end{aligned}$$

- unitarization gives a "short-cut" to higher-order matching
- usefulness is in the eye of the beholder (helpful for arXiv:1405.3607 study)

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## MinNLO<sub>PS</sub>: Drell-Yan



### Impact of shower recoil scheme

- shower suppresses configuration at large  $|\ln z|$
- due to the Pythia8 global recoil scheme
- effect is less pronounced if local recoil for emissions off initial-final colour dipoles
- these effects are formally subleading, but visible

Precision physics: %-level discussions!

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ongoing discussion:

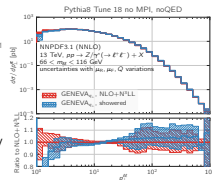
- What does "differential" mean? Can NNLO+PS be fully differential?
- Relation to/requirements from higher-precision showers
- historical baggage from NLO+PS starting point?

## Changing the resolution parameter: $q_T$

Using  $q_T$  as 0-jet resolution parameter allows for target N3LL<sub>res</sub>+NNLO<sub>0</sub> accuracy

- RadISH performs  $q_T$  resummation up to N3LL directly in  $q_T$  space  
Bizon et al. arXiv:1905.05171
- Its internal structure requiring Monte Carlo generation of unphysical events makes it hard to directly link.
- We proceeded building interpolating grids with Chebyshev polynomials and calling these interpolating grids from Geneva.
- Usage of Chebyshev polynomials is key in easily obtaining spectrum from cumulant.

- Results are in good agreement with dedicated RadISH+MATRIX N3LL+NNLO<sub>0</sub> control runs



Add observable-specific improved resummation.  
N<sup>3</sup>LL  $p_{\perp}, z$  possible!

rests the N3LL accuracy,

to simplify interface

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# Subleading color, non-global and super-leading logs

Context: Traditional PS are spin-averaged and “leading-color”. Several methods/codes to correct the color-factors of emission patterns exist. Non-global logarithms can be resummed by **PS-inspired methods**.

Color-correct no-emission pattern requires amplitude-level information.

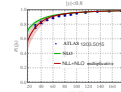
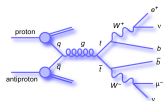
- Several proposals for completely new PS formalisms at amplitude level
- Embed QM interference at all orders.
- Enable description of Glauber phases, non-global logarithms and factorization-breaking effects.

DEDUCTOR most advanced public code. Other codes in the making.



# Progress on amplitude-level evolution

## NLL MC: top production with rapidity gap



Baleiger, TB, Ferroglia, 2006.00014

- Performed NLL resummation for a variety of observables
  - Gaps between jets in  $e^+e^-$  and  $pp$ , photon isolation cones, ...
  - Most recently: central jet veto in top production
    - massive partons, radiation from decay
- Shower as flexible Python library ngl\_resum, processes tree-level LHEF for LO  $\mathcal{H}_k$

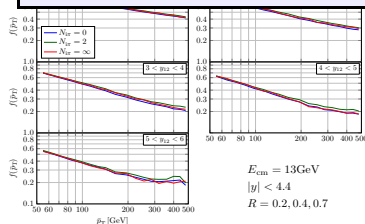
## Using PS methods for analytic resummation

## ongoing discussion:

- How do different formalisms compare to each other and to CSS or SCET?
- Define benchmark comparisons
- Status of implementation and potential for large-scale event generation

## Rapidity Gap Survival

### Inclusion of Glauber phases in differential code!



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## Collinear Subtractions



### Identify and subtract collinear singularities in soft evolution

[Forshaw, Holguin, Pläzer – JHEP 1908 (2019) 145]

$$\ln W_{AB} = \frac{\alpha_s}{2\pi} \sum_{i,j} T_i^a T_j^a \int_{\mu}^{\mu^2} \frac{d^2 k}{q^2} \int \frac{d^3 k}{2E} \frac{1}{\pi(S \cdot k)^2}$$

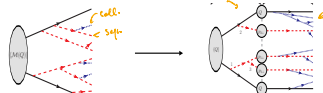
softness

ordering for soft evolution

$$\left( K^2(p_i, p_j; k) \frac{n_i \cdot n_j}{n_i \cdot n \cdot n_j} \delta(q^2 - K^2(p_i, p_j; k)) \theta_j(k) \right)$$

ordering for collinear evolution

$$\left( \frac{K^2(p_i; k)}{n_i \cdot n} \delta(q^2 - K^2(p_i; k)) \theta_i(k) - \frac{K^2(p_j; k)}{n_j \cdot n} \delta(q^2 - K^2(p_j; k)) \theta_j(k) \right)$$



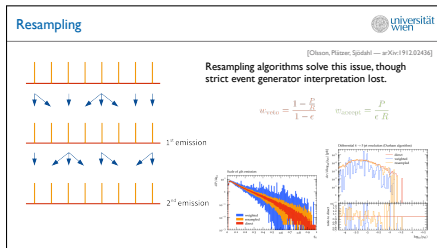
Amplitude-evolution splits into separate soft and collinear showers - like in factorization

# Progress on computational aspects

Warning: Experiments will only use better calculation if computationally feasible – basically, better theory should also be faster and more stable to replace older methods.

○ prototyping: often just focus on physics.  
weighted generation algorithms overcame many theory bottlenecks (negative kernels or “cross sections” ...)  
...at the expense of convergence.

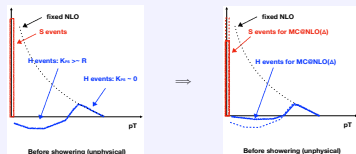
→ new/improved event generation algorithms crucial to support precision program in the future!



# Progress on algorithmic aspects

## MC@NLO- $\Delta$ (I)

- Main reasoning behind MC@NLO- $\Delta$ : suppress  $R - K_{PS}$  at small  $p_T$ .



- Suppression factor  $0 \leq \Delta \leq 1$ , with support in the  $n+1$ -body phase.
- $\Delta$  designed not to spoil any of the MC@NLO accuracy properties.

## Rethinking code factorization reduces neg. weights.

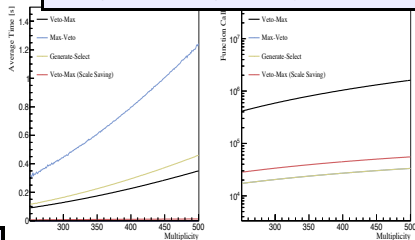
ongoing discussion:

- define the efficiency criterion for code deployment
- assess if new algorithms should be “open source” (nb:personal bias)
- new negotiations of factorization into fixed-order and all-order.

UCL

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## Changes in veto algorithms yield massive gains.



## The challenge: numbers

Say we take  $\lambda = \alpha_s L = 0.5$

| $\alpha_s$ | $L$  | $L + \delta L$ |
|------------|------|----------------|
| 0.04       | 12.5 | 32.5           |
| 0.02       | 25   | 45             |
| 0.01       | 50   | 70             |
| 0.005      | 100  | 120            |

- $\alpha_s \ll 1 \Rightarrow L \gg 1$
- Extra room to resolve emissions:  
 $\Rightarrow$  Shower cut should be smaller  
 $\Rightarrow$  extra  $\sqrt{\epsilon}$  ( $\delta L = \log(1/\epsilon)$ )

### Challenge 1:

Deal with numbers over large numerical range  $\Rightarrow$  precision impaired

### Challenge 2:

$g_1(\alpha_s L)L \gg 1 \Rightarrow \Sigma(\lambda, \alpha_s) \ll 1$   
 $\Rightarrow$  no events with standard “unweighted” techniques

(e.g.  $\lambda = 0.5, \alpha_s = 0.005 \Rightarrow \Sigma_{223}(L) \sim 10^{-29}$ )

True computing problem: special arithmetic for large numbers important

# Uncontroversial summary

- Precision MCs are a staple of LHC physics.
- NLO+PS is a solved<sup>1</sup> problem, and is undergoing computational consolidation.
- NNLO+PS has reached sophistication – but fully differential solutions are still missing.
- Showers have become a tool for high-precision resummation, both within PS and as helpers for analytic methods.
- With the current efforts, estimate that higher-log or higher-order parton showers will be the norm in  $\sim 5$  years.
- Monte-Carlo development has shed the reputation of “engineering” or “plumming”.
- We hope for more opportunities like the “[Taming the accuracy of event generators](#)” workshop

<sup>1</sup> sweeping statements should be scrutinized extra carefully.



## Provocative conclusion

- We cannot “do HEP” without MCs.
- We cannot “do LHC” without precision MCs.
- We cannot plan new machines w/o bleeding-edge precision MCs.
- We cannot do Snowmass projections with 10-year-old MCs.